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The Sub-tropical Jet-stream of the eastern North Pacific in January and April, 1952

by

H. D. Hoyle
(Meteorological Office)

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1. Introduction

It has been demonstrated by several writers, e.g. Gilchrist(1), Bannon(2) and Cressman(3), that the belt of strong westerly winds in the upper troposphere, known as the sub-tropical jet-stream, sometimes displays a two core structure. Bannon(2) shows that the eastern North Pacific in January and April is an area especially notable for this. One core is clearly associated with the polar front, but the other, nearer the Equator and at a higher level, is not so clearly associated with features of the surface synoptic weather map. Owing largely to the distribution of upper air reporting stations, most areas in which the high level winds of the sub-tropics have been investigated are ones in which, in winter, the land-sea distribution gives rise to semi-permanent troughs and considerable equatorward penetrations of polar air, making distinction between the two streams more difficult than in the area studied in this note.

The area considered and the observing stations used are shown in Fig.1. During April, 1952 an almost complete set of observations was available from all the stations shown. In January, 1952 observations were less complete and there were none from Ocean Weather Station "Q". Consequently, the analysis of the upper level charts is less trustworthy in January than in April, particularly in the north west portion of the area. To help in the construction of the mean and anomaly charts for January, values of contour height and temperature at a few latitude and longitude "grid" points were interpolated from the isopleths on the daily charts and their means calculated. April is therefore treated in rather greater detail in this note, January being used largely as confirmation.

As Fig.1 shows, the network of observations is very open. Fine methods of analysis are thus inappropriate and this study is therefore restricted to the major features.

2. Classification into types

Daily maps for 0300 G.M.T. were drawn of the contours at 500, 300, 200 and 150 mb. In addition, cross-sections were drawn, one or more per day. The plane of the cross-sections was not meridional but chosen to cut across the main flow, reported speeds being used and not components in any one direction. From these charts and cross-sections it was possible to find with reasonable accuracy the position of jet-stream cores on each day. The simplest method of distinction between the polar front jet and the sub-tropical jet was the pressure at the core. This was about 200 mb. for the sub-tropical jet and 300-350 mb. or even 400 mb. for the polar jet.

Fig. 2 and 3 show the daily positions of both cores. Positions of the polar front are also shown, these positions being taken directly from the analyses

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given in published charts in the "Daily Series Synoptic Weather Maps" of the U.S. Weather Bureau.

Study of Fig. 3 suggests classification of the April charts into three types as follows:-

Type 1 - A strong jet-stream roughly W.-E. near Hawaii and a separate polar front jet-stream clearly present to the north (3rd-5th, 11th-15th, 20th-23rd, 26th-30th).

Type 2 - A weaker sub-tropical jet-stream with a northerly wind component near Hawaii (1st, 2nd, 6th, 7th, 16th, 24th, 25th).

Type 3 - A sub-tropical jet-stream well north of its usual position (8th-10th, 17-19th).

The classification is, to some extent, subjective but the main features of Types 1 and 3 are readily recognisable and days not falling naturally into either of these types showed features in keeping with the definition of Type 2. The six days of Type 3 occurred in two spells of three days each and the seventeen days of Type 1 were in four spells of from 3-5 days each. The types occurred in some suggestion of a sequence, in that Type 2 followed Type 1 and preceded Type 3 on both occasions of a change from Type 1 to Type 3.

In order to represent diagrammatically the conditions prevalent in the three types mean cross-sections were drawn for each. The usual practice of plotting zonal wind components at appropriate latitudes on a meridional cross-section was thought to give an unsatisfactory representation of the conditions especially since, as noted previously by Bannon(4), strong northerly winds often exist near the Hawaiian Islands. Consequently, the mean cross-sections for each type were taken perpendicular to the axis of the jet-stream, the observations being grouped according to perpendicular distance from the jet-stream core. Reported wind speed was thus used directly. Where a second (polar front) jet-stream was also present, a separate mean cross-section for the type was drawn in a similar manner relative to this core. The two were then combined into one diagram for each type by using the mean latitude of the surface position of the polar front as a basis of reference and placing the jets at their mean distances from this position.

The resulting cross-sections are shown as Fig. 4(a), (b), (c). It is clear from the method of construction that although the scale of distance is quite precise the latitudes are only approximate, since the cross-sections are not strictly meridional. This does not interfere, however, with the assessment of wind shear.

The January charts (Fig.2) are more complex. There is little doubt that two separate jet-streams exist on the first fifteen days. During these days there is no certain evidence of the conditions classified as Type 3, but the days 2nd-5th show reported winds of 100 kt. or more and clearly can be classified as Type 1. The remainder of the 15 days can be classified as Type 2. Mean cross-sections (Fig. 5(a) and (b)), prepared as before, are very similar to those of equivalent type in April.

From 16th-22nd January, 1952 the synoptic situation is disturbed in the Hawaii area by the formation of a "kona" storm (see, for example, Palmer(5)). As this is a somewhat special situation these days are not analysed in detail. From 23rd-31st January, 1952 the daily maps show only one jet-stream core, the type of flow pattern common in other longitudes. This has been called Type 4 and the appropriate mean cross-section for this type is shown at Fig.5(c).

3. Discussion of the cross-sections

In the types which show two clearly separate jet-stream cores (Types 1 and 2) the following major points are apparent, from Fig. 4 (April):-

/(i)

(i) There seem to be three tropopause levels defined by the temperature field; a tropical tropopause at about 90 mb., a polar tropopause (poleward of the polar front) at about 300 mb. and an intermediate or sub-tropical tropopause at about 200 mb.

(ii) Just as the polar front jet-stream has its core at about the same level as the tropopause poleward of the polar front, so the sub-tropical jet-stream has its core at about the same level as the sub-tropical tropopause on its poleward side.

The following features suggested by the mean cross-sections were more apparent on the cross-sections for individual days:-

(iii) The sub-tropical jet-stream is associated with a baroclinic zone. Unlike the baroclinic zone associated with the polar front this sub-tropical baroclinic zone is most marked between 400 and 200 mb. with virtually barotropic conditions at lower levels.

(iv) It appears that this sub-tropical baroclinic zone is connected with the temperature minimum associated with the sub-tropical tropopause. As pointed out by the writers of "The Jet Stream"(6) the fact that at 200 mb. the temperature is lower at about 30-40°N. than at any other latitude is a feature which calls for some explanation and cannot be dismissed purely in terms of advection from other latitudes. The cross-sections suggest that this temperature minimum may be more clearly defined when the sub-tropical jet-stream is strong (Type 1).

When there is only one jet-stream (Type 4) the intermediate sub-tropical tropopause is absent and there is no sign of any temperature minimum at or near the 200 mb. level (see Fig.5(c)). It seems, therefore, that the existence of this temperature minimum at 200 mb. (and the associated three-tropopause scheme) may be an essential requirement for a sub-tropical jet-stream separate from the polar front jet-stream.

4. The horizontal temperature distribution

It is evident from the foregoing discussion that strong winds are associated with baroclinic zones and this suggests that the geostrophic approximation through the thermal wind relation may be roughly valid even at latitudes as low as 20°N. There is thus some prospect that the variations in position and intensity of the sub-tropical jet-stream may be understood if the variations in horizontal temperature gradient can be demonstrated and explained. The cross-sections show that the 400-200 mb. layer is the significant one as regards the thermal wind contribution. Consequently, attention is directed to the 300 mb. and 250 mb. temperatures. Fig. 6 shows the 300 mb. temperature distribution for April, 1952, Fig. 6(a) being the mean for the month and Fig.6(b), (c) and (d) showing the mean isotherms for Types 1, 2 and 3 respectively. The dotted isopleths on Fig. 6(b), (c) and (d) show the anomaly from the mean for the month. Fig. 7 shows similar charts for the 250 mb. level.

It is at once apparent that whereas Fig.6(a) displays a fairly steady N.-S. temperature gradient at 300 mb., Fig.7(a) shows that the temperature minimum associated with the sub-tropical tropopause is apparent at 250 mb. The sequence of Types (1-2-3-1 etc.) is noticeable, particularly at 250 mb., by the manner in which the coldest air is displaced eastwards (i.e. down-stream) from Fig.7(d) to 7(b) to 7(c). The steep temperature gradient near Hawaii for Type 1 is clearly shown in Fig.6(b). The northerly component characteristic of Type 2 is shown in Fig.6(c) and the belt of thermal contrast at about 40°N. for Type 3 is indicated in Fig.6(d). Fig.6(d) also gives a strong thermal gradient near Hawaii where, as inspection of Fig.3 for 17th, 18th, 19th shows, a residual sub-tropical jet-stream can still exist despite the re-creation of the main sub-tropical jet-stream further north. (Note that to avoid undue complication this

/residual

residual low latitude stream is not shown in Fig.4(c) which does not extend south of about 30°N.)

That the thermal wind relation holds approximately, down to 20°N., is borne out by the daily values in Fig.8(b) and (c). Fig.8(b) shows the maximum reported wind speed in the sub-tropical jet-stream near Hawaii, whilst Fig.8(c) shows the reported temperature difference between Hilo and Lihue. Now a temperature difference of 2.5°C. between these stations at all levels from 500-200 mb. would be equivalent to a geostrophic thermal west wind of about 100 kt. through this layer. There is clearly a rough similarity between the two curves (correlation co-efficient .49) and the mean values of temperature difference and wind speed are approximately equal to those which the geostrophic relation requires.

The temperature anomalies (Fig.6 and 7) show that, in the central portion of the area considered, temperatures are below normal during Type 1 and above normal during Type 3. The broad features of the observed temperature distribution and anomalies would be obtained if a portion of the monthly mean charts were displaced southward in Type 1 and northward in Type 3. Type 2 could be an intermediate stage in which the southward displacement is in the east of the area and the northward displacement in the west of the area. This suggests that horizontal advection may be an important factor in the type transitions.

Fig.9 shows isotherms for January, 1952 at 250 mb. Fig.9(a) shows the mean isotherms for the first 15 days. This is the mean for the days on which there were two separate jet-streams and is thus comparable with the mean for April, 1952. Fig.9(b) shows the mean for Type 1 during January, 1952, the dotted isopleths being the anomaly from the 15-day mean of Fig.9(a). Although based on only 4 days, features similar to all those pointed out for Type 1 during April are readily apparent. As the mean chart Fig.9(a) is almost entirely Type 2 no separate diagram for Type 2 is given.

It is interesting to note the different temperature field during the period January 23rd-31st which was characterised by a single jet-stream, (Type 4). Fig.9(c) gives the mean for the month of January excluding the days affected by the "kona" storm, i.e. a 24-day mean chart. Fig.9(d) gives the mean for Type 4, the dotted isopleths being the anomaly from the 24-day mean. The absence of the area of minimum temperature shown on all other 250 mb. temperature charts is very striking and agrees with the deduction from the cross-section Fig.5(c).

5. Geostrophic advection

Mean contour maps for the 200 mb. level are shown at Fig.10. Fig.10(a) shows the mean chart for the month of April, 1952, whilst Fig.10(b), (c) and (d) show, respectively, the mean contours for Types 1, 2 and 3. The dotted isopleths on these latter charts show the height anomalies from the mean for the month. Fig.11 shows similar charts for the 500 mb. level.

In view of the strong zonal component over most of the area the essential features of meridional geostrophic advection show more clearly in the anomaly patterns. It is clear that in the region of 40°N. 160°W. Type 1 is characterised by a N.-S. flow component and Type 3 by a S.-N. flow component at the levels which contain the sub-tropical baroclinic zone. These appear not only in the mean charts but also in the daily charts.

A simple index of the N.-S. geostrophic flow in this area is given by the contour height difference between 40°N. 150°W. and 40°N. 170°W. The daily values of this index (positive for flow from N.-S.) are shown at Fig.8(d) and (e) for the 500 and 300 mb. levels respectively. This index was measured in hundreds of metres per 20° of longitude (at 40°N.) so that an index value of 1 corresponds to a mean geostrophic flow of about 13 kt. Comparison with

/Fig.8(a)

Fig.8(a) and (b) confirms the suggested association between the N.-S. flow component and the type. It is further suggested that a strong N.-S. flow component is associated with a strong jet-stream and in this connection it may be noted that the correlation co-efficient between N.-S. flow index at 500 mb. and maximum reported speed in the jet-stream near Hawaii was .52.

Following the discussion in the previous section and comparing Fig.7 and 10, the geostrophic advection anomalies for the three types are such as to deform the mean temperature field in roughly the manner which is, in fact, observed.

An attempt was made to assess the advective temperature change directly using a geostrophic scale on the 300 mb. height and temperature isopleths. The process was found to be inaccurate and too easily affected by the subjective judgment of the analyst, and was therefore abandoned. As the usual method of assessing vertical motion is dependent upon an estimate of the temperature change due to horizontal advection no reliable analysis of the vertical motion was possible from the available data.

A more crude, but considerably more objective, method of estimating the advective temperature change at 300 mb. was then tried. If I is the N.-S. index of flow at 300 mb. and Δ_i ($i = 1, 2, 3$) is the N.-S. temperature gradient in this area read from the mean charts for the three types, then $-I\Delta_i$ is of the nature of an advective change of temperature. With I measured as indicated earlier and Δ_i measured in °C. per 10° of latitude, $-(1/2)I\Delta_i$ gives this rate almost exactly in °C. per 24 hours. Daily values of $I\Delta_i$ are shown in Fig.8(j). The dotted curve in Fig.8(j) shows the actual 24-hour temperature change (since 0300 G.M.T. on the previous day) at 300 mb. These latter values are for 35°N. 150°W., roughly the position of maximum temperature anomaly as shown by Fig.6. They were read from the isotherms and may well have an error of 1°C. or so owing to the open network of observations. (It will be noted that in Fig.8(j) the scale for the actual temperature change is on the right and is twice as large as the scale for $I\Delta_i$. Note also that the zero of the observed change (δT) has been plotted to correspond with the mean value of $I\Delta_i$ (equal to 1.5) and not with $I\Delta_i$ equals 0). Close agreement between the two curves cannot be expected since the method ignores temperature changes due to W.-E. advection, but Fig.6 suggests that this may only be important on isolated days, notably during Type 2 conditions. Nevertheless the curves of Fig.8(j) show fair agreement in regard to both the occurrence and the magnitude of points of maximum and minimum.

The data for January show the same broad features of the contour patterns as those observed in April. Fig.12(a) shows the mean contours for the first 15 days of January, 1952 whilst Fig.12(b) shows the mean for Type 1 and its anomaly from the 15-day mean. The stronger jet-stream days are again associated with a marked N.-S. advection anomaly reasonably near to 40°N. 160°W., the slightly different position and orientation of this anomaly being in keeping with the slightly different position of the negative temperature anomaly in Fig.9(b) compared with that of Fig.7(b).

It is interesting to note conditions above the tropical tropopause. Fig.13 shows 60 mb. charts for April, 1952 giving the temperature and contour height means (and anomalies from the mean for the month) for Type 1 and Type 3. The height anomalies are similar in general character to those at lower levels and once again the temperature anomalies are not incompatible with those which might be expected as a result of the advection anomalies.

Although the effects of vertical motion may not be negligible there is thus considerable evidence suggesting that during the existence of two separate jet-stream cores the variations in position and intensity of the sub-tropical jet-stream are largely controlled on a day-to-day basis by geostrophic advection of the temperature field.

6. Related features of the surface synoptic chart

Daily values of some parameters from the surface synoptic charts during

/April,

April, 1952 are included in Fig.8. These values were taken directly from the published maps in the "Daily Series Synoptic Weather Maps" of the U.S.W.B. which are for 1230 G.M.T. They are accordingly plotted on the time scale mid-way between the plots of the 0300 G.M.T. values for the other graphs. Fig.8(f) shows the latitude of the polar front at or near 150°W. As the polar front marking successive outbreaks of cold air (compare Palmén(7)) usually advances roughly from NW. to SE., latitudes of the polar fronts were sometimes measured at 160°W. early in a polar outbreak and at 140°W. in the later stages of such an outbreak. Measurements at different longitudes are distinctively marked. It is noticeable that at the beginning of each period of Type 1 there is a cold front in about latitude 40°N. The converse is not however true, i.e. each cold front crossing 40°N. does not coincide with the beginning of a Type 1 period.

Fig.8(g) and (h) show the longitudes of cold and warm anticyclones (situated respectively to north and south of the polar front). These show a remarkable correspondence between cold anticyclones reaching longitude 175°W. and the beginning of Type 1. Serebreny(8) pointed out the importance of an anticyclone in such longitudes to the accurate forecasting of the polar front jet-stream. It would seem to play an equally important role in the formation of a strong sub-tropical jet-stream.

Fig.14 shows mean surface charts (including mean frontal positions) for the month of April, 1952 and for the three types during that month. Mean surface pressure values were computed at 10° latitude and 10° longitude grid points from the surface maps published in the "Daily Series Synoptic Weather Maps". Mean frontal positions were obtained by averaging the longitudes at which the front intersected specified lines of latitude. It will be seen that the features of polar front and anticyclone positions mentioned in the two previous sub-paragraphs as associated with the onset of Type 1 conditions are clearly shown in Fig.14(b). It is noticeable too that the N.-S. advection component near 40°N. 160°W. characteristic of the upper level flow during Type 1 is also evident at the surface, and similarly for the S.-N. advection during Type 3.

A further point of interest is observed if the mean frontal positions for Types 1, 2 and 3 are compared with the horizontal temperature distribution shown in Fig. 6 and 7. The major cold front on each chart of Fig.14 has been denoted by the letter M showing E.-W. progression in the previously noted sequence of Types 3-1-2 etc. It will be seen that the major frontal region coincides with the lowest temperatures at 300 and 250 mb. - the trough in the isotherms being over the frontal zone rather than behind it over the low level cold air mass. This was quite noticeable on the daily charts.

Surface charts for January, 1952 are shown at Fig.15. Fig.15(a) shows the 24-day mean (i.e. mean for the month excluding only the "kona" storm days) whilst Fig.15(b), (c) and (d) show the mean charts for Types 1, 2 and 4 respectively. The positions of the polar front and anticyclone cell for Types 1 and 2 are similar to those for April. The most striking feature of Fig.15, however, is that for Type 4 (the single jet-stream type) there is no sub-tropical high pressure cell. It is also noticeable that polar air has penetrated well south.

7. Relation to the general (meridional) circulation

Fig.16 shows the model of the general meridional circulation proposed by Palmén(7); this is considered as a mean for all longitudes. Such mean meridional flow is therefore essentially ageostrophic, as opposed to the local day-to-day geostrophic meridional motion considered in Section 5. Fig.16 also includes a sketch of the mean temperature distribution for all longitudes. It is apparent that the regions of low temperature associated with the tropical and sub-tropical tropopauses are situated above the regions of tropical and frontal ascent respectively. Whether or not these regions of cold air are the result of adiabatic cooling on ascent is a

/matter

matter for conjecture. The vertical motion associated with the polar front is in the mean largely a result of the dynamically driven ascent in frontal depressions, and adiabatic cooling shown by the mean isotherms thus seems a likely result in this region. The local existence of cold air in the upper troposphere above the polar front has already been pointed out and thus the association of the two can be accepted, even if the causal relation is in doubt.

It will also be seen that the meridional circulation is such as to give confluence and hence a steepening of the horizontal temperature gradient at just the levels and latitudes at which the sub-tropical baroclinic zone exists on occasions of the two-jet structure. It also gives diffluence and hence a slackening of the horizontal temperature gradient in the lower levels of this region where observations suggest that conditions are largely barotropic. It would seem, therefore, that the meridional circulation involved in the usual concept of a sub-tropical high pressure belt to the south of the polar front region may be important in producing the type of temperature distribution associated with a sub-tropical jet-stream separate from the polar front jet-stream. This is borne out by Fig.15(d) which shows a complete breakdown of the usual polar front - sub-tropical anticyclone relationship during the period in which there is only one jet-stream in this region.

8. Conclusions

1. The area of the Pacific considered frequently shows in January and April two separate jet-streams; one associated in conventional manner with the polar front having a core at about 300 mb., the other often a thousand miles or more to the south of the polar front with a core at about 200 mb.

2. Both jet-streams show speeds in excess of 100 kt. on some days with pronounced shear in both the horizontal and vertical. The more southerly of the two streams weakens considerably at times and becomes a very broad stream with speeds of the order of 50-75 kt. and with little shear in the horizontal.

3. The two-jet type of flow is associated with a characteristic temperature distribution with three distinct tropopause levels - a tropical tropopause at about 90 mb., a sub-tropical tropopause at about 200 mb. and a polar tropopause at about 300 mb.

4. Day-to-day variations in the speed of the more southerly of the two jet-streams seem to be dependent, through the geostrophic relation, upon day-to-day changes in the temperature field largely brought about by geostrophic meridional advection.

5. The temperature distribution characteristic of the two-jet type of flow may well be a result of the ageostrophic meridional circulation accompanying the maintenance of a sub-tropical high pressure belt to the south of the general polar front and frontal depression region.

6. From the very limited number of occasions studied the occurrence in this region of a single jet type of flow appears to accompany a breakdown in the sub-tropical high pressure belt with extensive equatorward penetration of polar air. The three tropopause temperature structure also breaks down under these circumstances by the disappearance of the sub-tropical tropopause.

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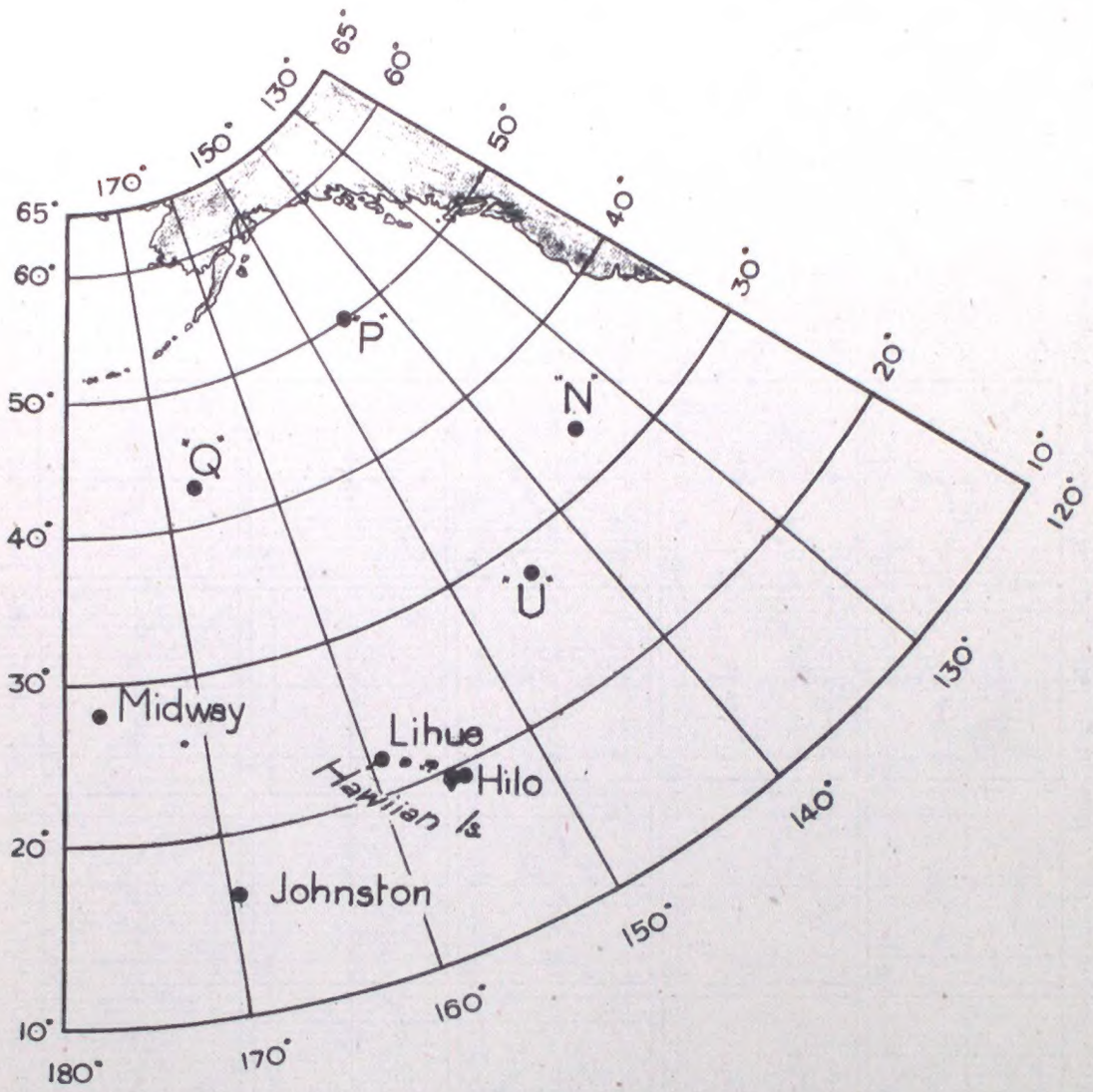


"P", "Q", "U", "N", denote ocean weather ships

Fig. 1

DAILY SCHEMATIC CHARTS 0300 G.M.T. JANUARY, 1952

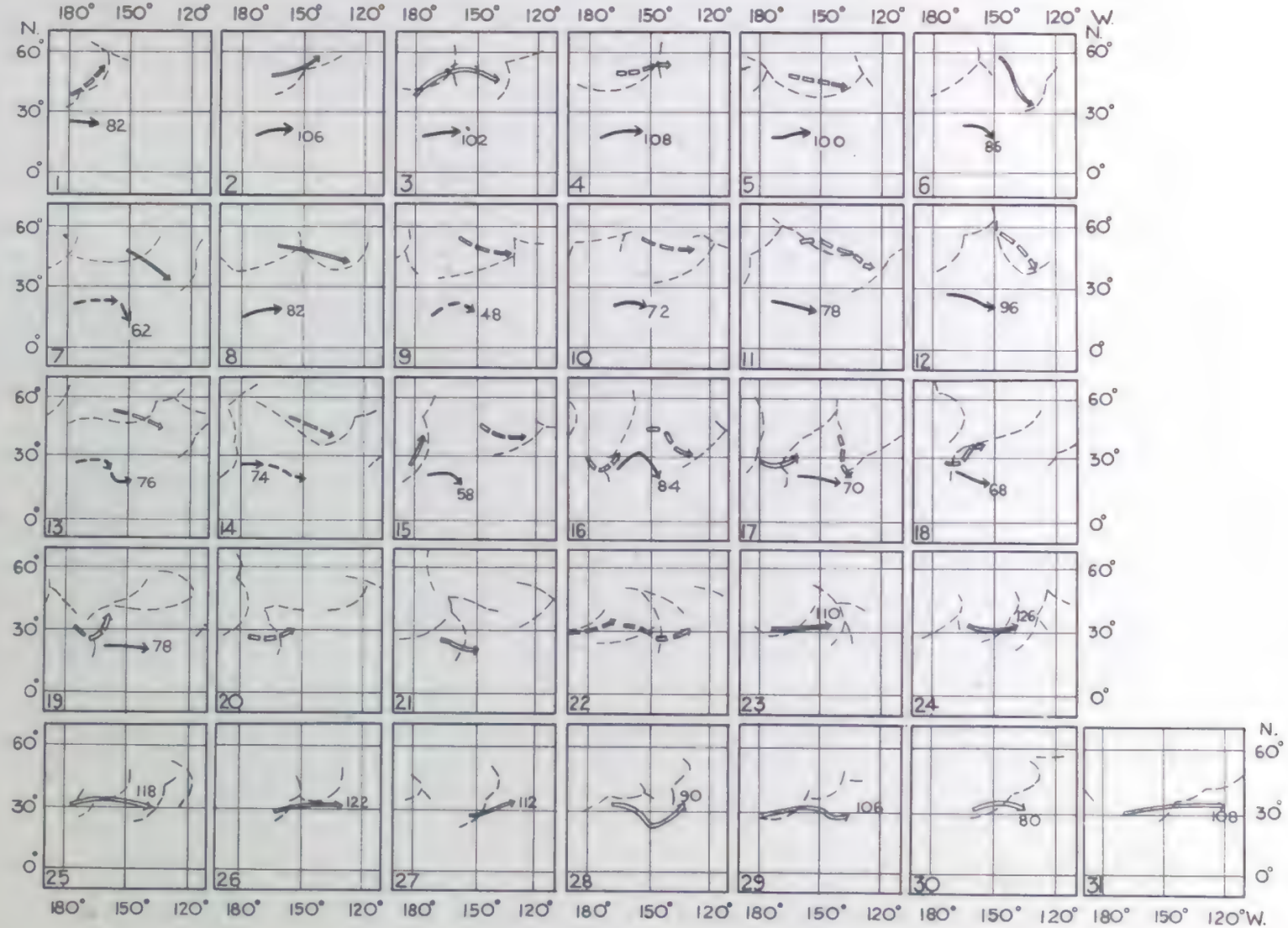


Fig 2

Core of maximum winds at about 200 mb.

Core of maximum winds at about 300-400 mb.

Possible cores with maximum reported speed in kt.

Possible cores.

Polar front.

DAILY SCHEMATIC CHARTS 0300 G.M.T. APRIL, 1952

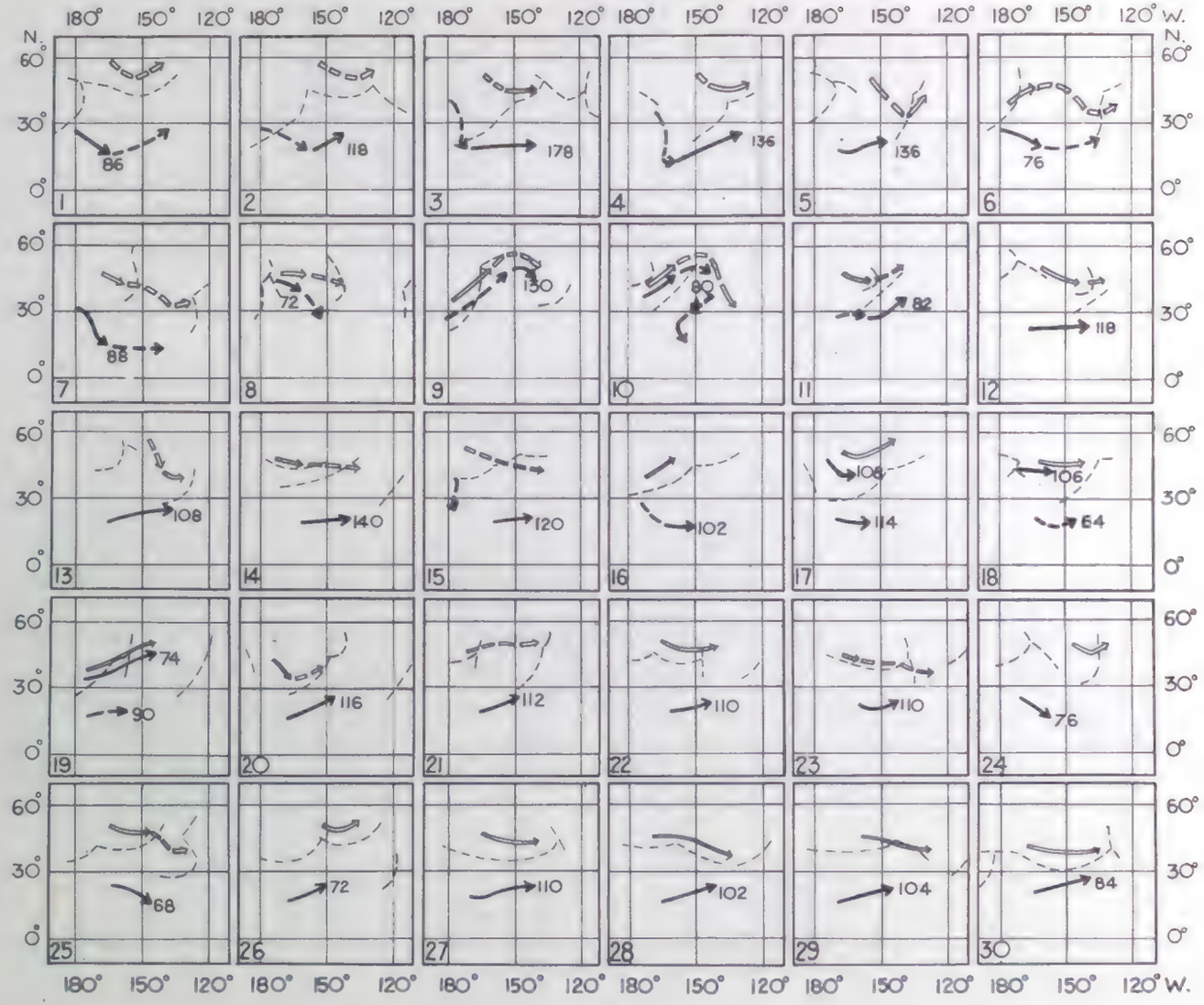


Fig. 3

Core of maximum winds at about 200mb. Possible cores with maximum reported speed in kt.

Core of maximum winds at about 300-400 mb. Possible cores. Polar front

APRIL 1952
VERTICAL CROSS-SECTIONS

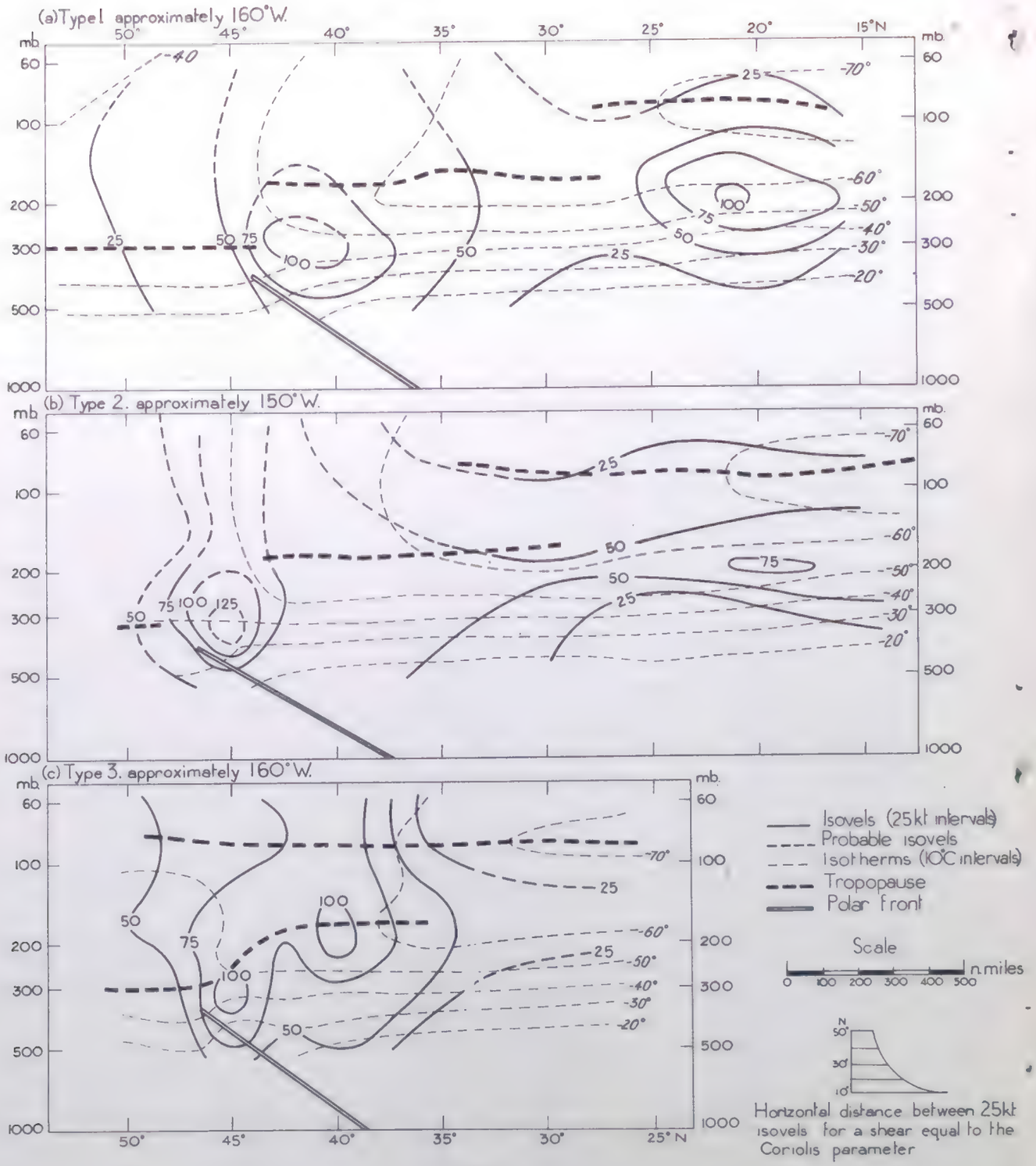


Fig. 4

JANUARY 1952
VERTICAL CROSS-SECTIONS

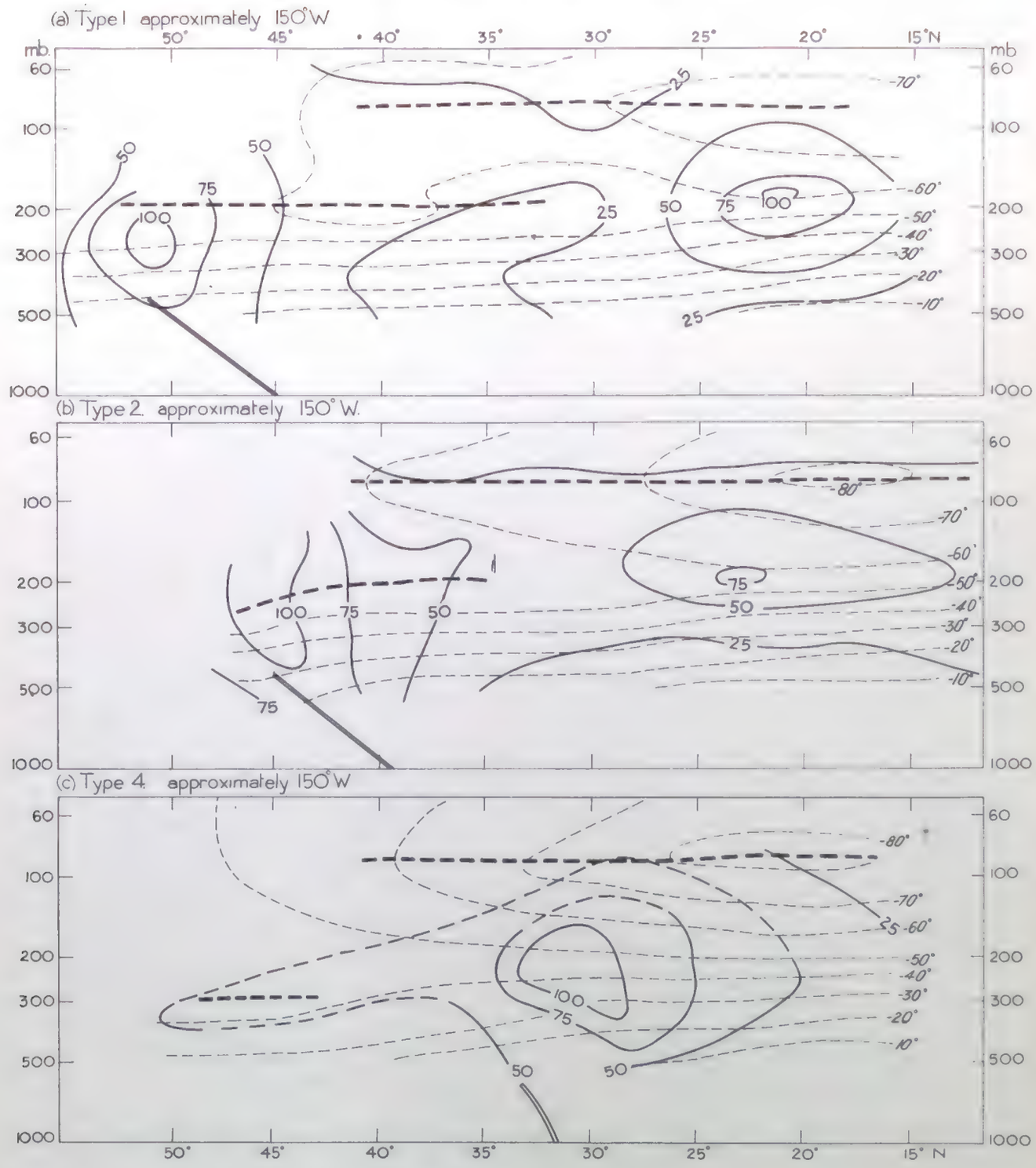
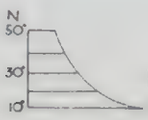


Fig. 5

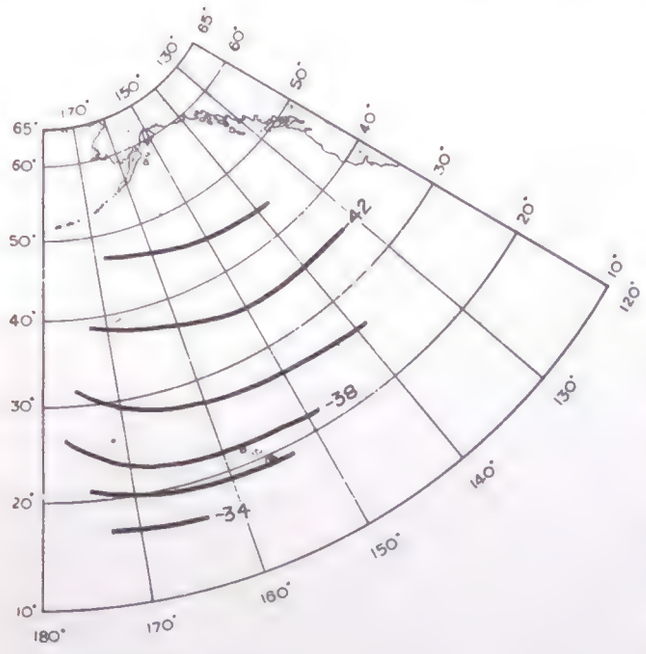
Isovels (25kt intervals) — — Probable isovels . . . . Isotherms (10°C intervals) — — — Tropopause
Polar front



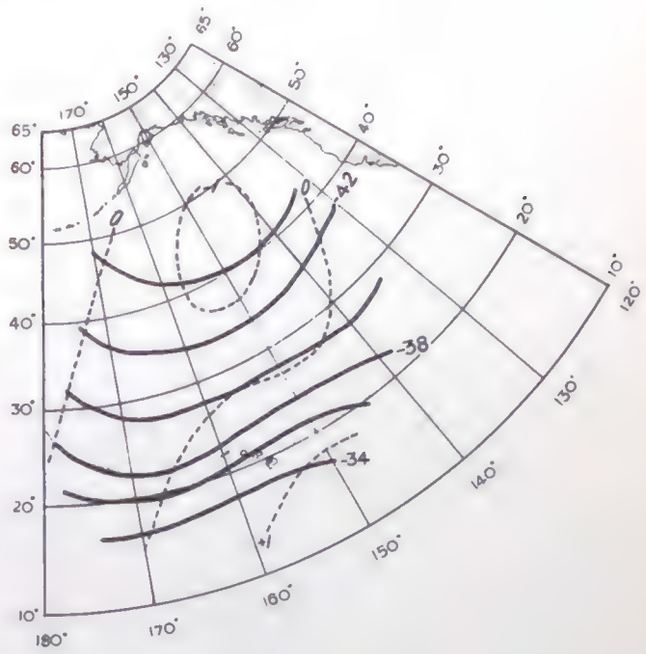
Horizontal distance between 25kt. isovels for a shear equal to the Coriolis parameter

Scale
0 100 200 300 400 500 n miles

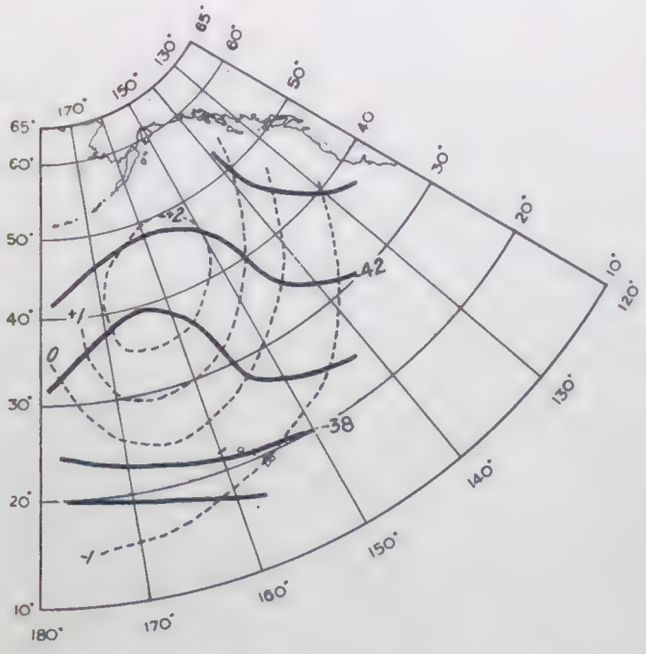
APRIL 1952
300 mb. ISOTHERMS (°C)



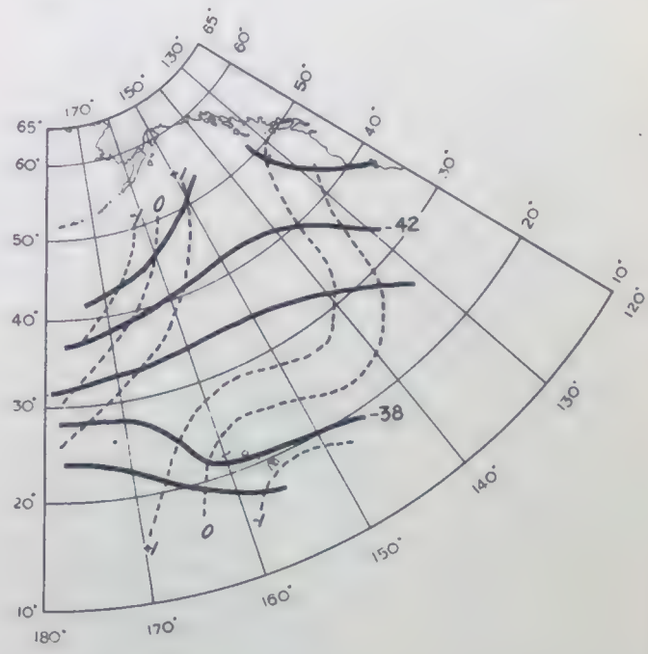
(a) Mean for April



(b) Mean for Type 1.



(c) Mean for Type 2



(d) Mean for Type 3.

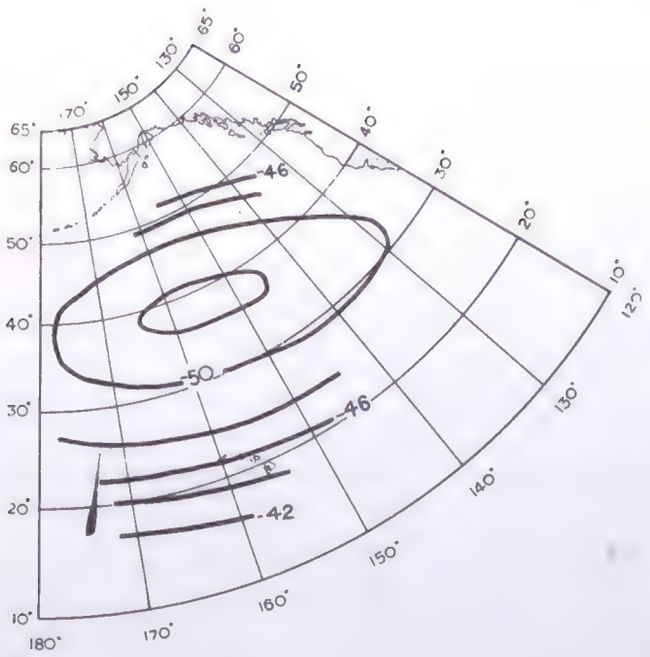
Fig. 6

——— Isotherms (2°C intervals)

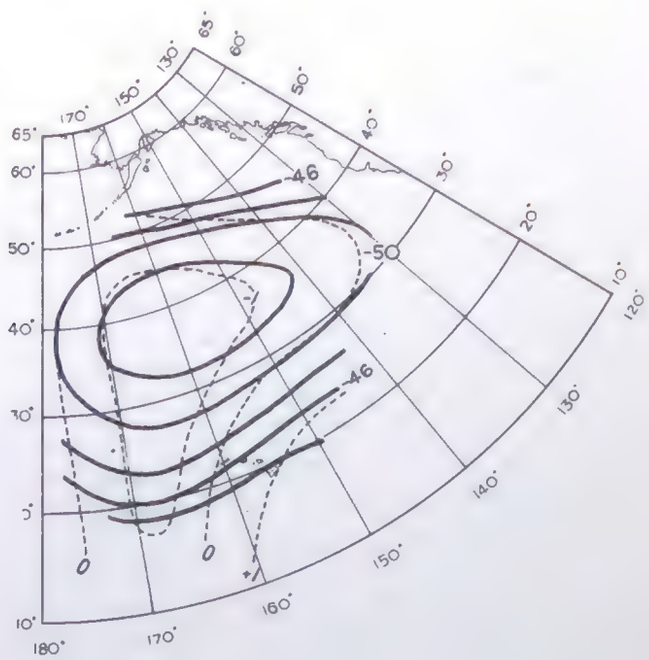
- - - - - - - - Anomalies (1°C intervals)

APRIL 1952

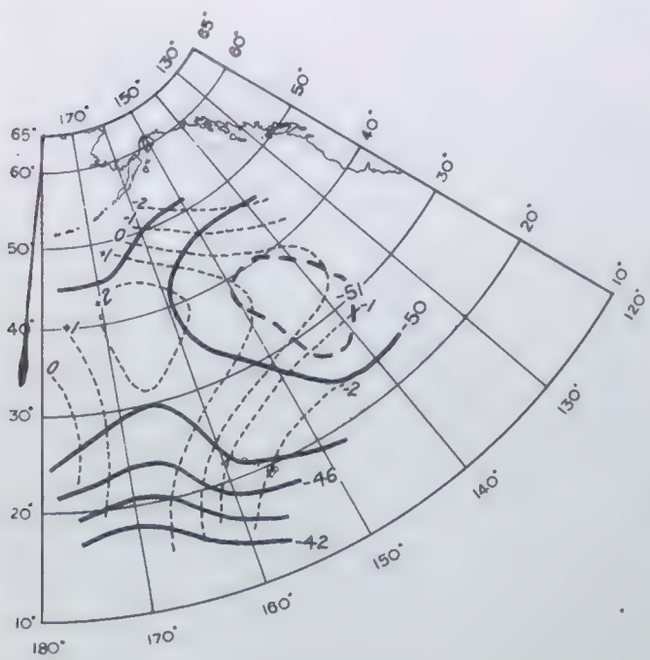
250mb. ISOTHERMS (°C)



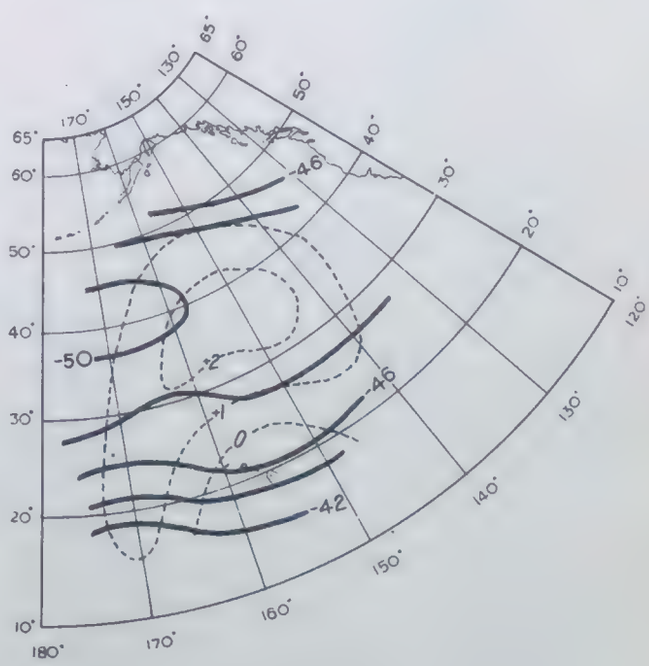
(a) Mean for April



(b) Mean for Type 1



(c) Mean for Type 2



(d) Mean for Type 3

Fig. 7

——— Isotherms (2°C intervals)

- - - - - - - - - Anomalies (1°C intervals)

DAILY VALUES OF VARIOUS PARAMETERS

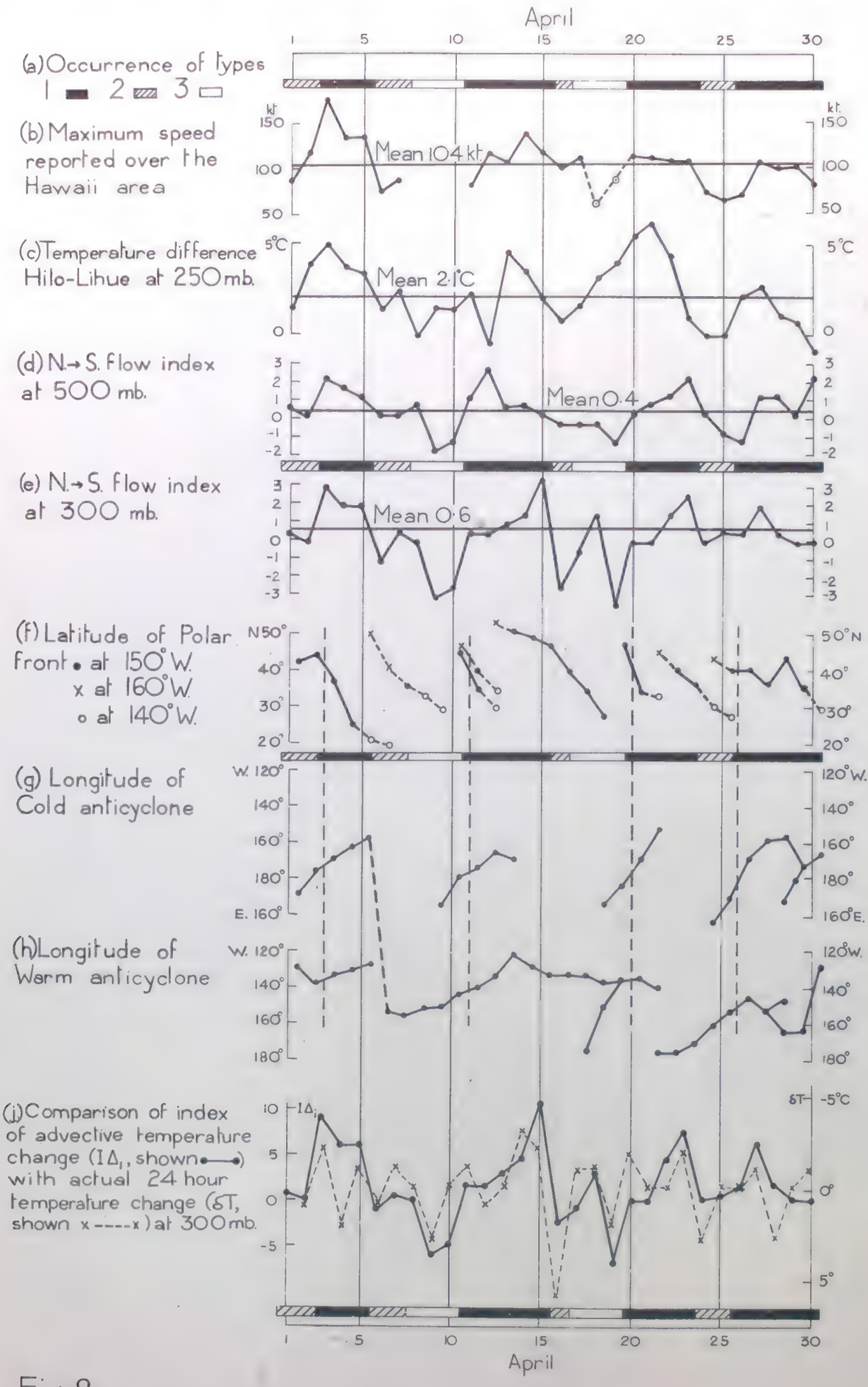
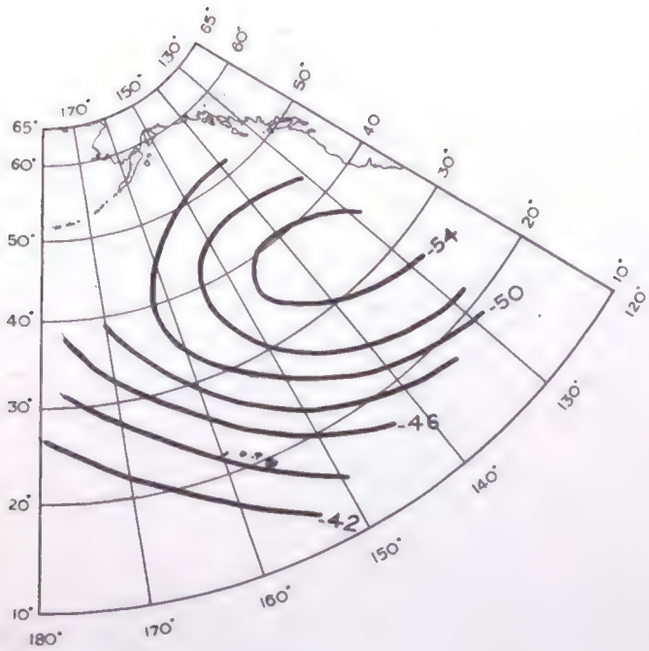
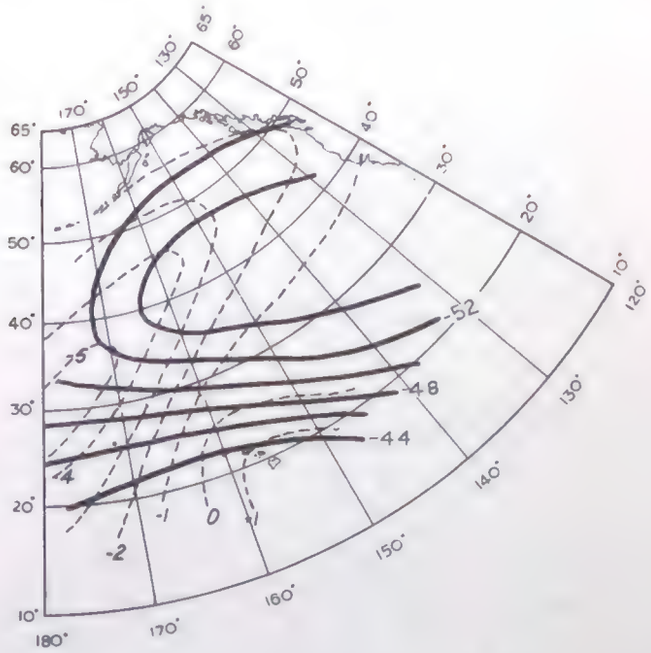


Fig. 8

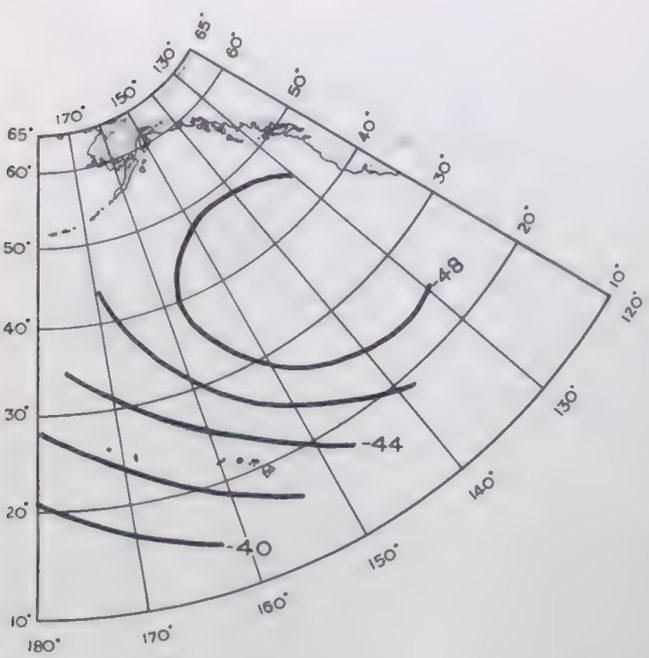
JANUARY 1952
250mb ISOTHERMS (°C)



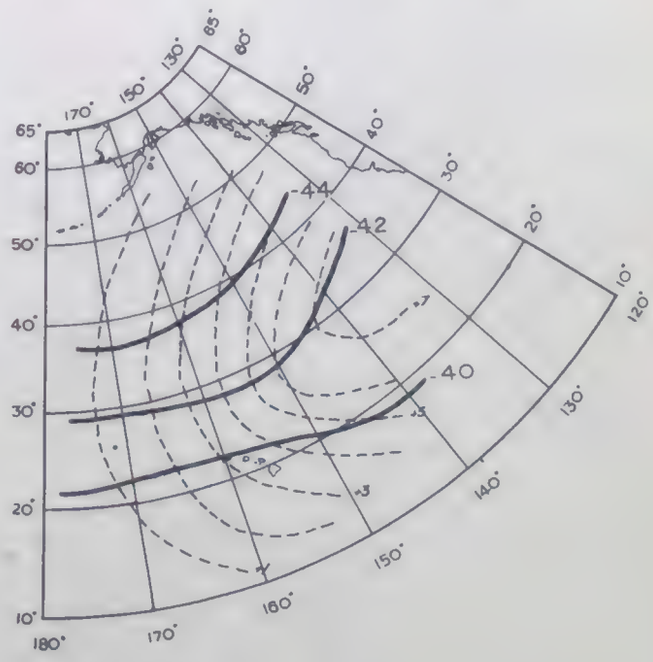
(a) Mean, January 1st–15th



(b) Type 1. Mean and anomaly from Fig. 9(a)



(c) 24 day mean ("kona" storm days omitted)

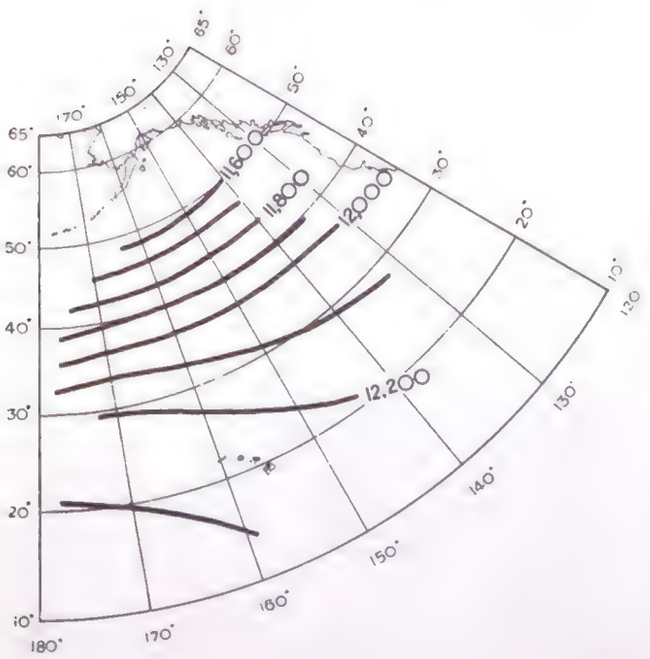


(d) Type 4. Mean and anomaly from Fig. 9(c)

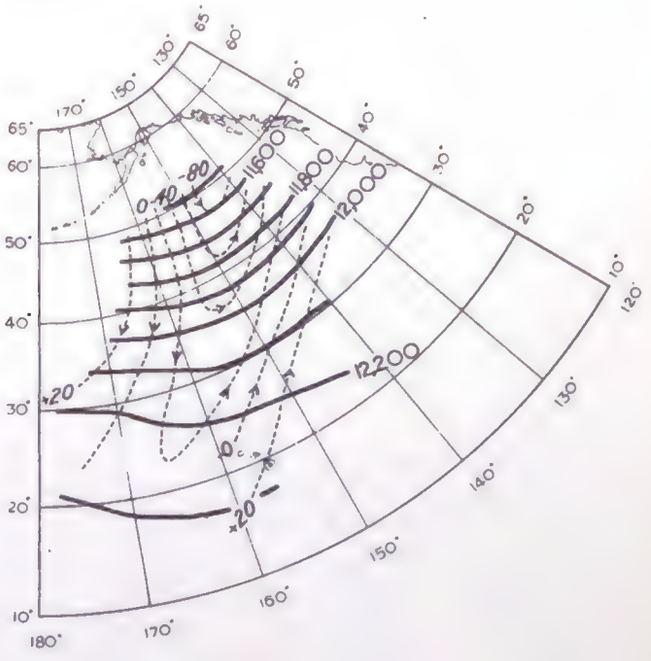
Fig. 9

——— Isotherms (2°C intervals)
– – – – – – Anomalies (1°C intervals)

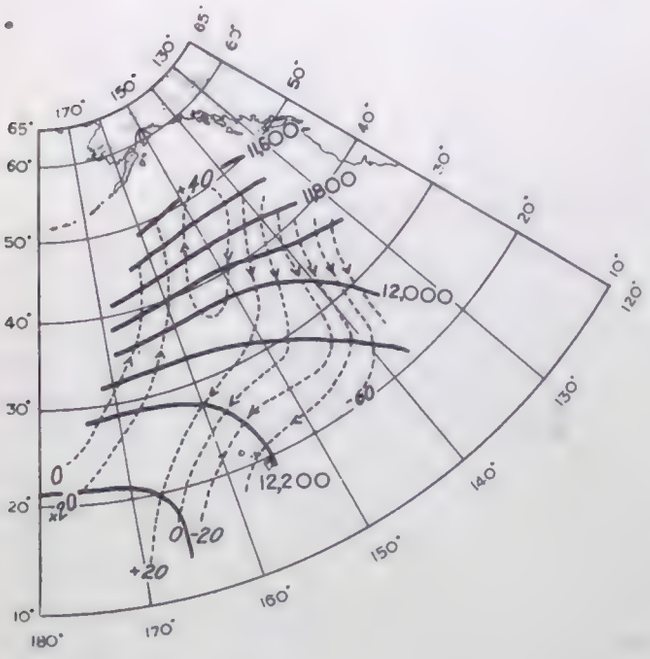
APRIL 1952
200mb. CONTOURS (metres)



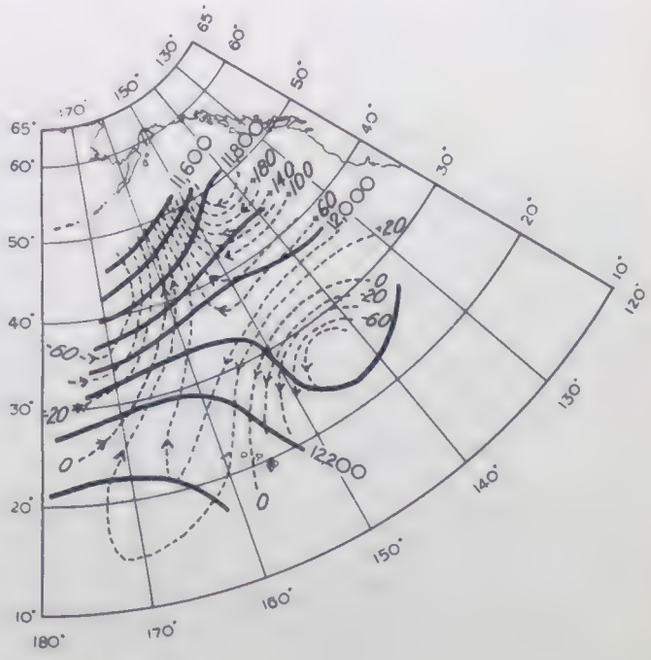
(a) Mean for April



(b) Mean for Type 1.



(c) Mean for Type 2.



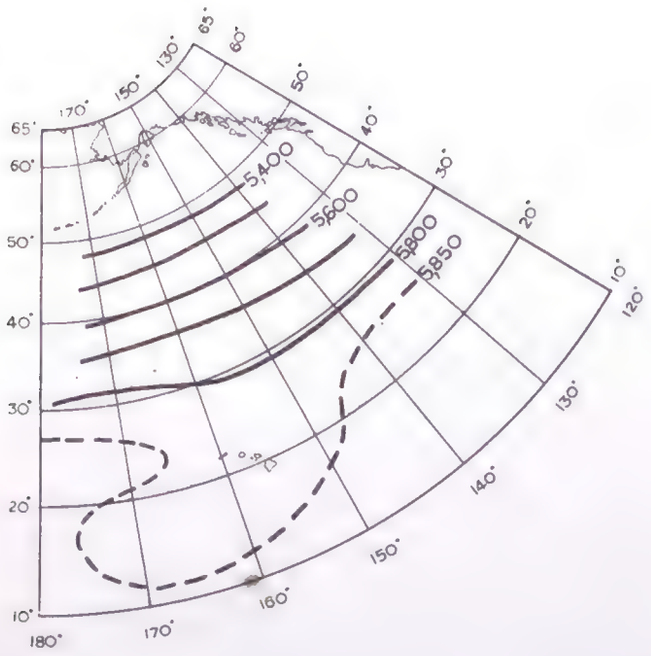
(d) Mean for Type 3.

Fig. 10

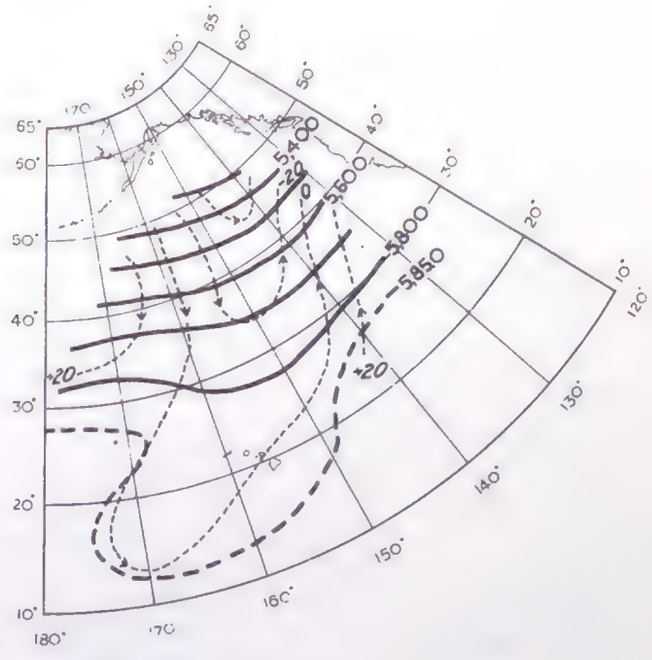
——— Contours (100 metre intervals)
- - - - - - - Anomalies (20 metre intervals)

APRIL 1952

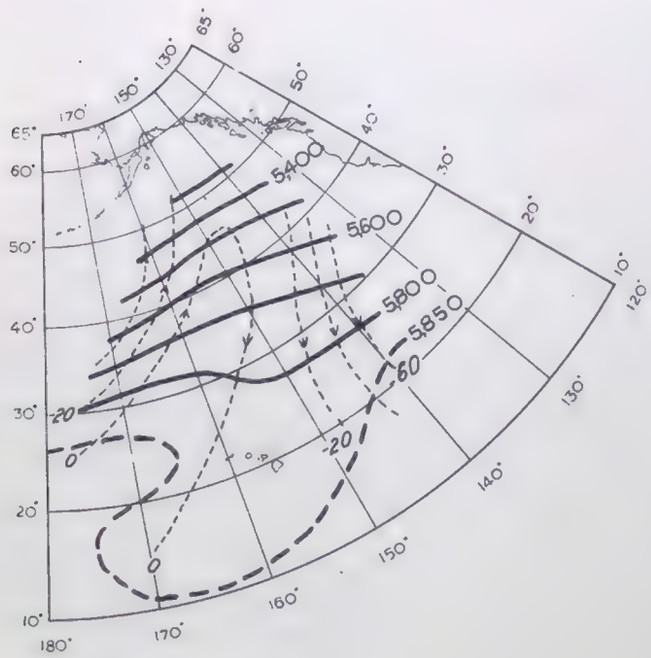
500 mb. CONTOURS (metres)



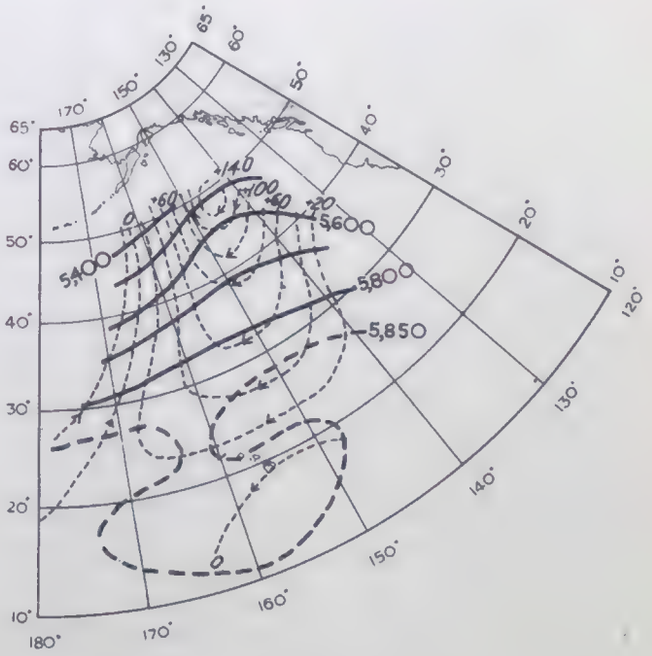
(a) Mean for April



(b) Mean for Type 1



(c) Mean for Type 2.



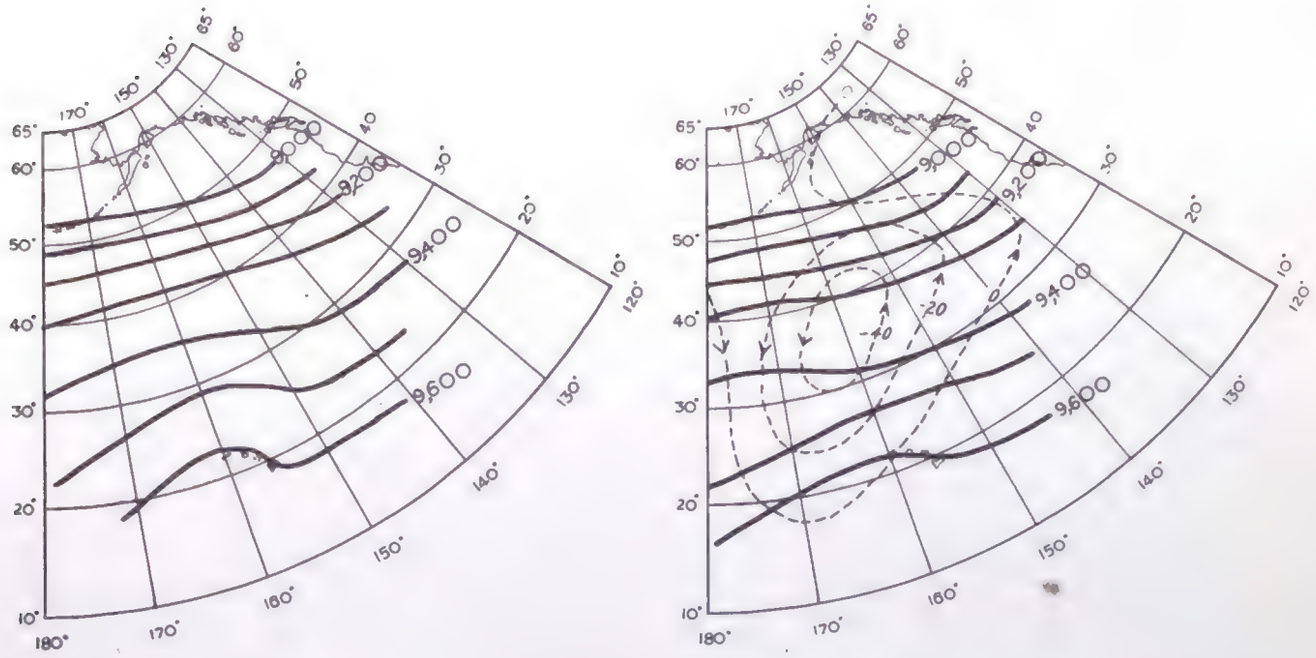
(d) Mean for Type 3.

Fig. 11

——— Contours (100 metre intervals)

---------- Anomalies (20 metre intervals)

JANUARY 1952
300 mb CONTOURS (metres)



(a) Mean for January 1st - 15th

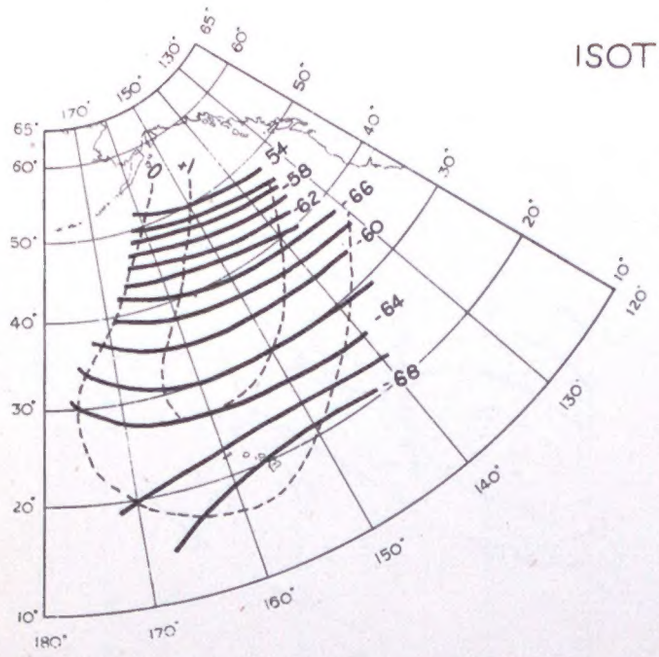
(b) Mean for Type I.

Fig. 12

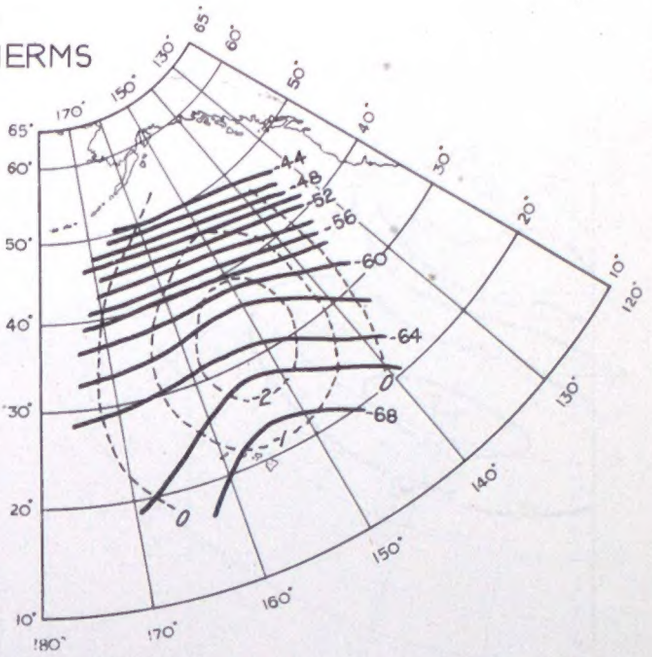
—— Mean contours (100 metre intervals)
---- Anomalies from Fig. 12 (a) (20 metre intervals)

APRIL 1952
60mb.

ISOTHERMS

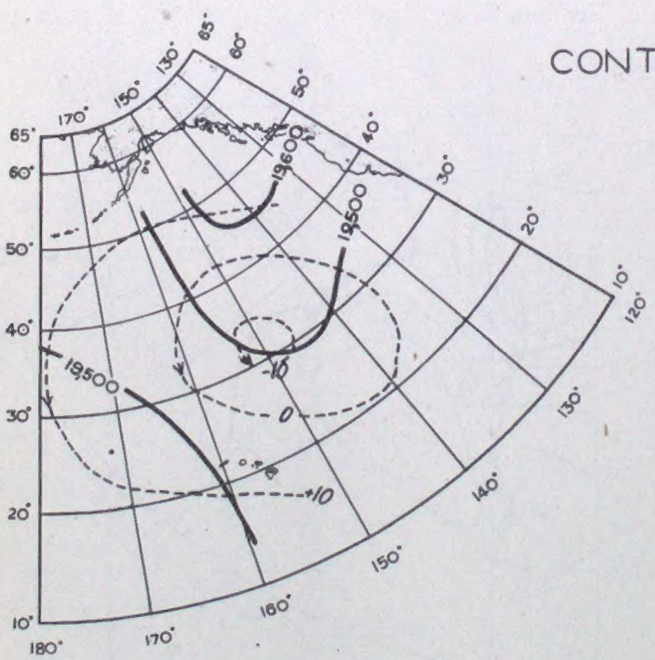


(a) Mean for Type 1

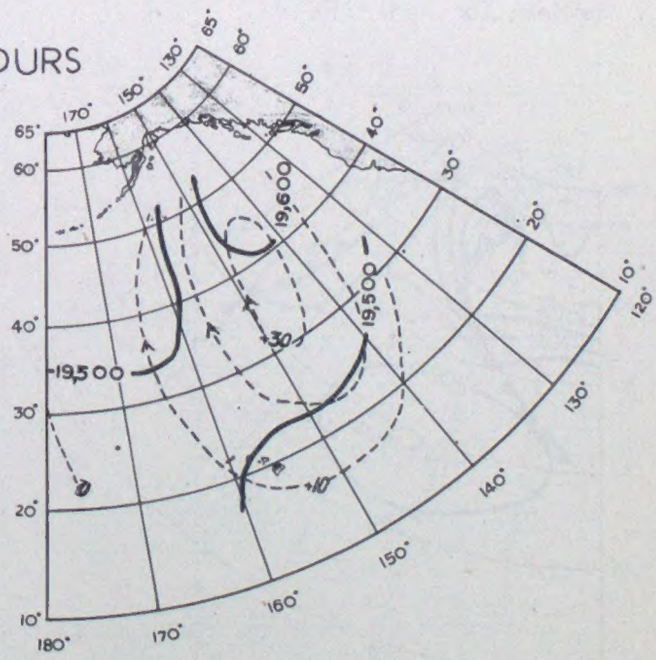


(b) Mean for Type 3

CONTOURS



(c) Mean for Type II

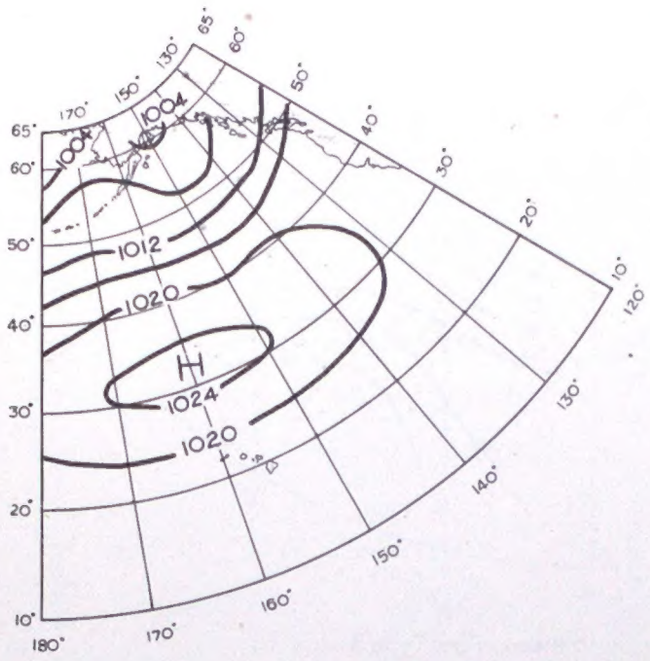


(d) Mean for Type 3

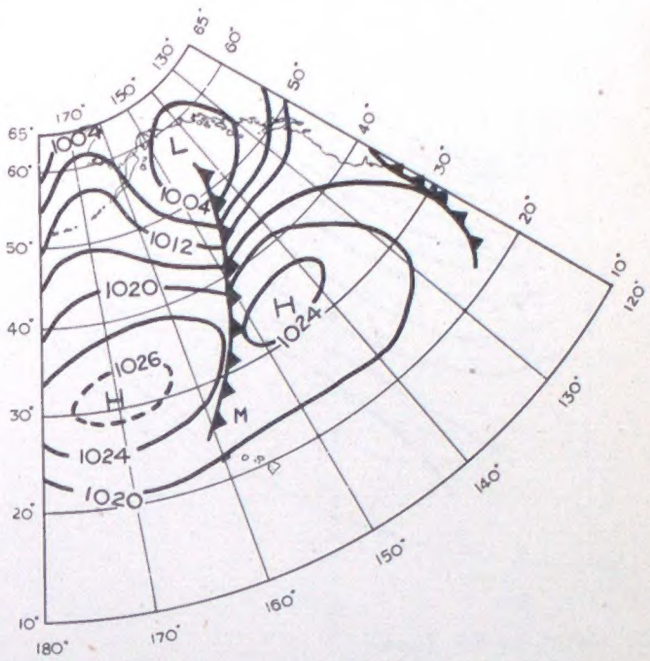
Fig 13

——— Isotherms (2°C intervals) - - - - - Anomalies (1°C intervals)
——— Mean contours (100metre intervals). - - - - Anomalies (10metre intervals)

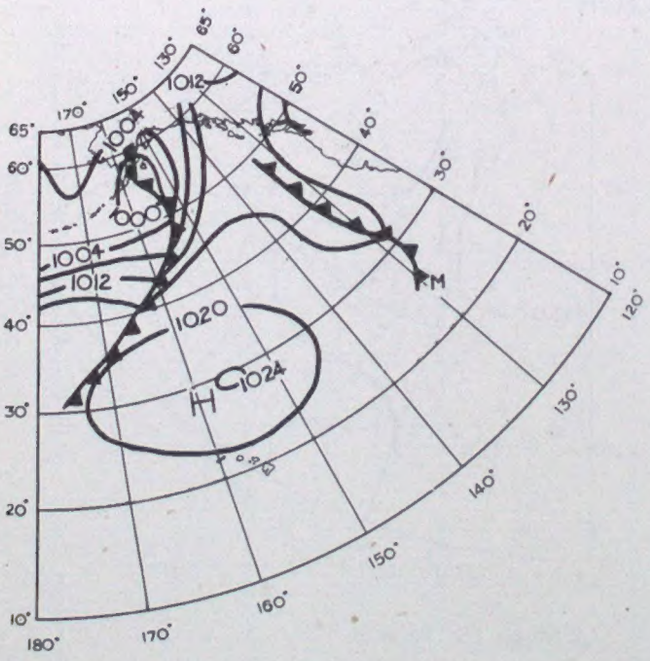
APRIL 1952
MEAN SURFACE ISOBARS (mb.)



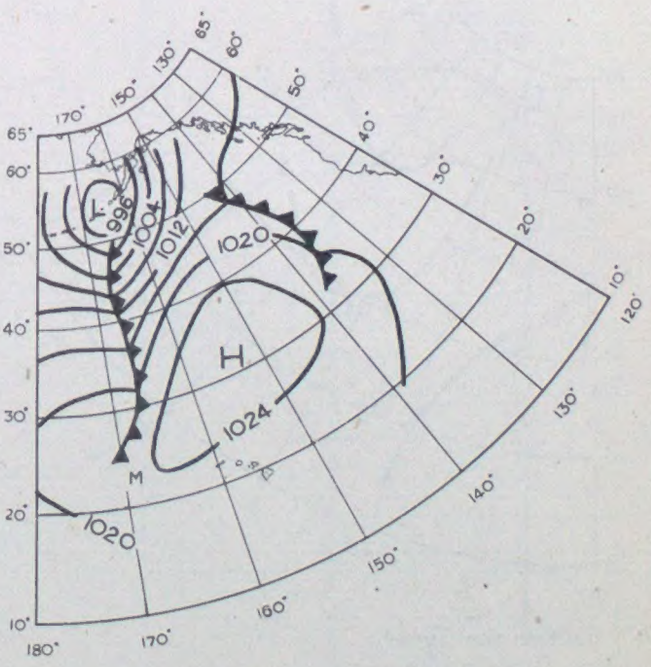
(a) Mean for April 1952



(b) Mean For Type I



(c) Mean for Type 2



(d) Mean for Type 3

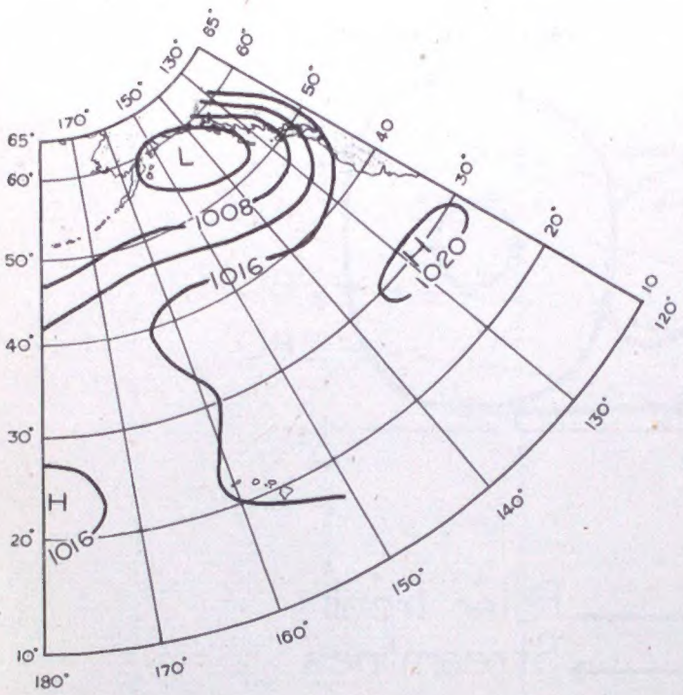
Fig. 14

Isobars (4 mb. intervals)

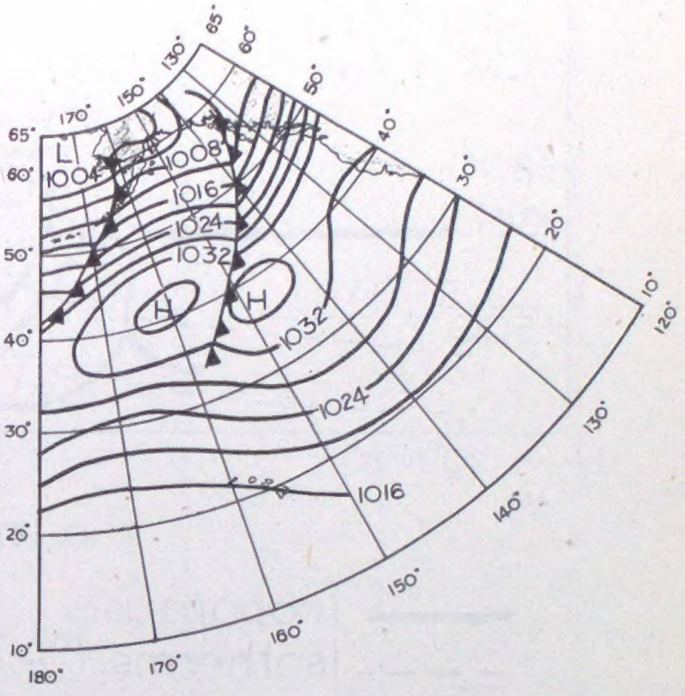
Polar fronts

M Major cold front

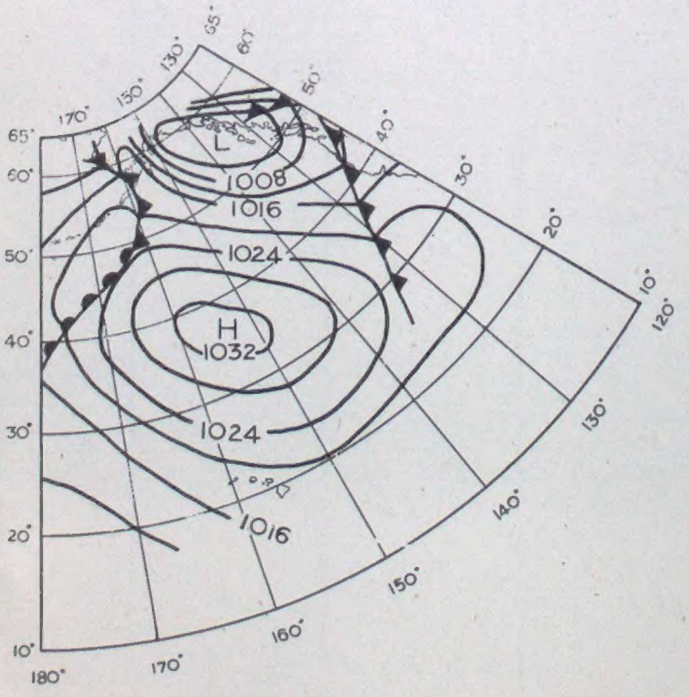
JANUARY 1952
MEAN SURFACE ISOBARS (mb)



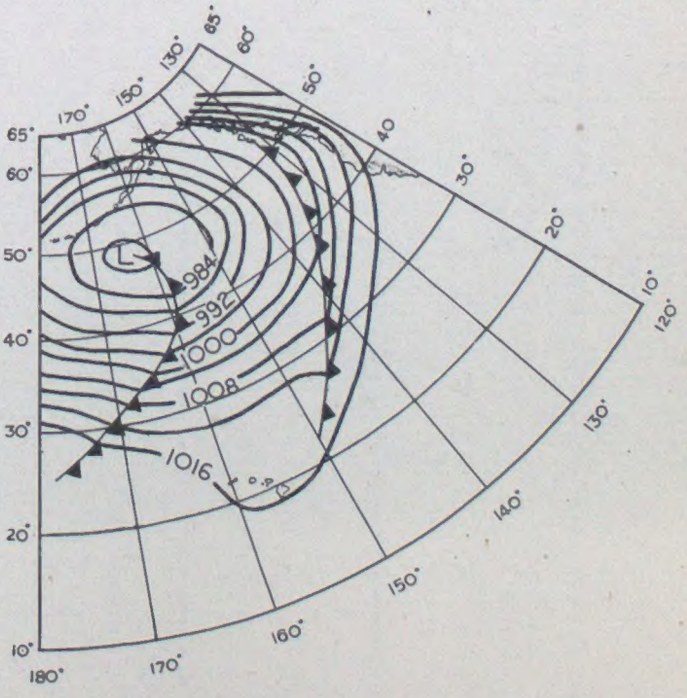
(a) Mean (24 day) for January



(b) Mean for Type 1.



(c) Mean for Type 2



(d) Mean for Type 4

Fig. 15

Isobars (4 mb intervals)

Polar fronts

General meridional circulation (after Palmén)

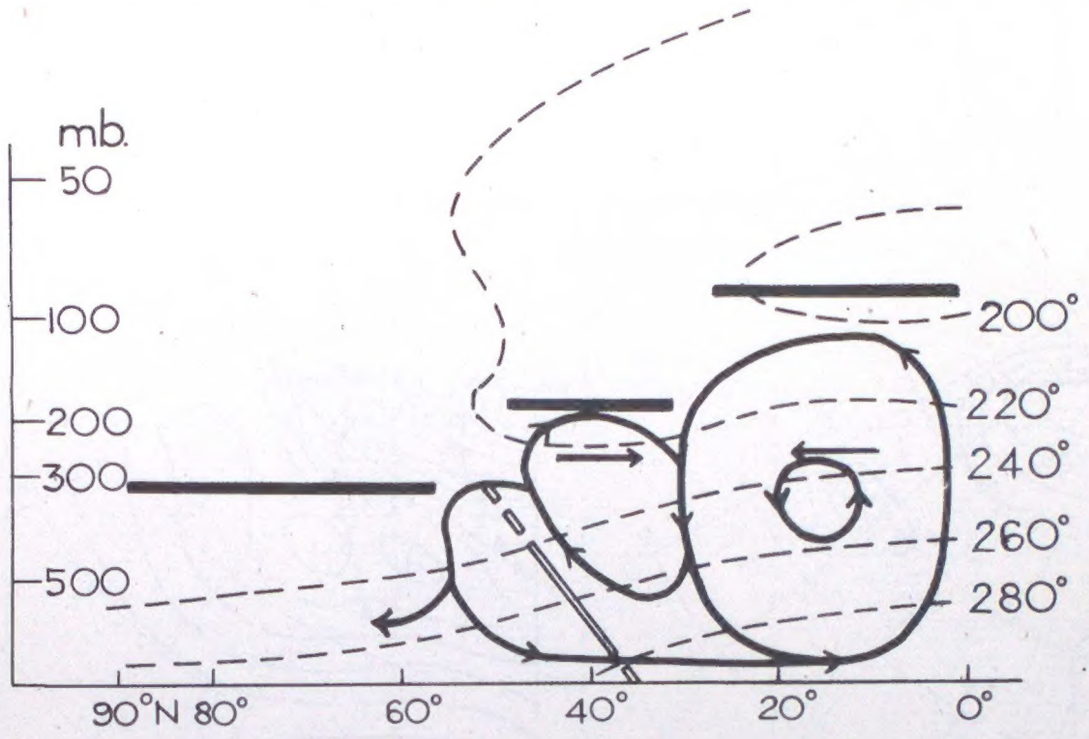


Fig. 16

Tropopause — Polar front
Isotherms (°A) — Streamlines